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A Broadband and High-Gain Metamaterial Microstrip Antenna

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14. ABSTRACT A broad bandwidth and high gain rectangular patch antenna was specifically designed in this project using planar-patterned metamaterial concepts. Based on an ordinary patch antenna, the antenna has isolated triangle gaps and crossed strip-line gaps etched on the metal patch and ground plane, respectively. Demonstrated to have left-handed characteristics, the patterned metal patch and finite ground plane form a coupled capacitive-inductive circuit of negative index metamaterial. It is shown to have great impact on the antenna performance enhancement in terms of the bandwidth significantly broadened from a few hundred MHz to a few GHz, and also in terms of high efficiency, low loss and low voltage standing wave ratio. Experimental data show a reasonably good agreement between the simulation and measured results. This antenna has strong radiation in the horizontal direction for some specifical applications within the entire band.					
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Abstract

A broad bandwidth and high gain rectangular patch antenna was specifically designed in this paper using planar-patterned metamaterial concepts. Based on an ordinary patch antenna, the antenna has isolated triangle gaps and crossed strip-line gaps etched on the metal patch and ground plane, respectively. Demonstrated to have left-handed characteristics, the patterned metal patch and finite ground plane form a coupled capacitive-inductive circuit of negative index metamaterial. It is shown to have great impact on the antenna performance enhancement in terms of the bandwidth significantly broadened from a few hundred MHz to a few GHz, and also in terms of high efficiency, low loss and low voltage standing wave ratio. Experimental data show a reasonably good agreement between the simulation and measured results. This antenna has strong radiation in the horizontal direction for some specific applications within the entire band.

0.1 Acknowledgments

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0.2 Resultant Direct and Indirect Publications

Resulted in from the supported Projects: AOARD-07-4024 and AOARD-09-4069, the following research papers were published:

- Le-Wei Li, Ya-Nan Li, Tat-Soon, Yeo, Juan R. Mosig and Olivier J.F. Martin, "A Broadband and High-gain Metamaterial Microstrip Antenna," *Applied Physics Letters*, vol.96, no. 6, 164101, April 2010

- Li Hu, Le-Wei Li, and Raj Mittra, “Electromagnetic Scattering by Finite Periodic Arrays Using CBFM/AIM,” *IEEE Transactions on Antennas and Propagation*, vol. 58, to appear, 2010
- Wei-Jiang Zhao, Le-Wei Li, and Li Hu, “Efficient Current-Based Hybrid Analysis of Wire Antennas Mounted on a Large Realistic Aircraft,” *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 8, August 2010
- Wei-Jiang Zhao, Le-Wei Li, and Ke Xiao, “Analysis of Electromagnetic Scattering and Radiation from Finite Microstrip Structures Using an EFIE-PMCHWT Formulation,” *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 7, July 2010
- There are a few other papers completed and submitted to journals for publications. They are still under-review and thus are not listed herewith.

0.3 Background Introduction

A microstrip patch antenna [1, 2] represents one of the most commonly utilized printed antennas in practice. It enjoys its advantages of low profile, simple structure, low cost, and omnidirectional radiation patterns [1, 2]. A narrow bandwidth is, however, the main drawback of the microstrip patch antennas. Some approaches have been therefore developed for bandwidth enhancement [3–6]. Among those common ones, one is to increase the height of the dielectric substrate while the other is to decrease the substrate dielectric constant. Certainly, the latter will induce the matching circuits to be impractical due to excessively wide lines designed.

Usually microstrip patch antennas have the strongest radiation in the vertical direction (while the patch is placed horizontally). At the mean time, the radiation along the plane of patch usually causes unwanted radiated power (due to surface waves such as lateral waves and leaky waves) and thus causes coupling among array elements so as to reduce the efficiency [4]. Dielectric polarization currents were confirmed as the physical sources of this unwanted radiation. In practical specific applications, it is, however, desirable to have the radiation along the horizontal plane.

Since the artificial left-handed materials (LHMs) or metamaterials were proposed, theoretically characterized, and experimentally realized [7–13], scientists and engineers have tried various ways to bring these special material characteristics into practical applications. The metamaterials have been successfully applied in optical frequency band for optical imaging [14–17]. Although it is easier to realize metamaterials in microwave frequency region for negative refractions, there was still little progress toward practical applications [18]. At microwave frequencies, potential applications include primarily (a) substrate materials for

antenna and microwave component designs and fabrications, and (b) absorbing materials for engineering and radar applications. For example, split ring resonators (SRRs) [11,19–21] and some other planar structures [22–24] were applied in some antenna fabrications to minimize the size and enhance the radiation. Also in some other designs, artificial magnetic materials [10,25] with stacks of SRRs under patch antenna were proposed and it was found that the resonant frequency of the original patch antenna can be significantly reduced [26]. There are, however, still primarily fundamental issues at microwave frequencies: narrow bandwidth (when both negative permittivity and negative permeability merge in the same band) and high loss (due to the ohmic loss and radiation loss of inclusion elements), and this drawback becomes especially serious when the SRR- and other inclusion-types of metamaterials are used as substrate of the patch antenna.

The objective of this paper is thus to enhance, in a completely different approach, the bandwidth and gain of a conventional patch antenna by applying the planar metamaterial patterned structures directly on the upper patch and bottom ground of the dielectric substrate, so the patch antenna can have an excellent performance.

0.4 Proposed Structure of Single-Element Antenna and Metamaterial System

A conventional microstrip patch antenna is usually mounted on a substrate and backed by a conducting ground plane. In the present investigation, as shown in Fig. 1, a planar left-handed material pattern on the rectangular patch antenna mounted on the substrate is designed to enhance its horizontal radiation as well as to broaden its working bandwidth via its coupling with the conducting ground backed to the substrate and patterned in a different way. On the upper patch, the periodic gaps are designed in the form of isolated micro-triangles; while on the bottom ground plane, as shown in Fig. 1(a), periodically distributed cross strip-line gaps are designed. To maintain the transmission consistency of input energy, the metal in and around the feed-line area is, however, not etched. The prototype and the dimension of the two patterned planes of the proposed antenna are shown in Fig. 1. The left-handed characteristics of these patterns were already demonstrated in [27] and thus will not be further discussed here. We have also optimized the original patterns slightly to achieve a better performance of the antenna. Physically, the upper patch and bottom plane are coupled to form a capacitive-inductive (C-L) equivalent circuit and thus can induce backward wave which travels along the plane of patch. In this connection, the radiation along the patch direction is significantly enhanced.

A conventional antenna of the same size is used as a reference for comparison and both the conventional rectangular patch and the proposed patch antenna are fed by an off-centered

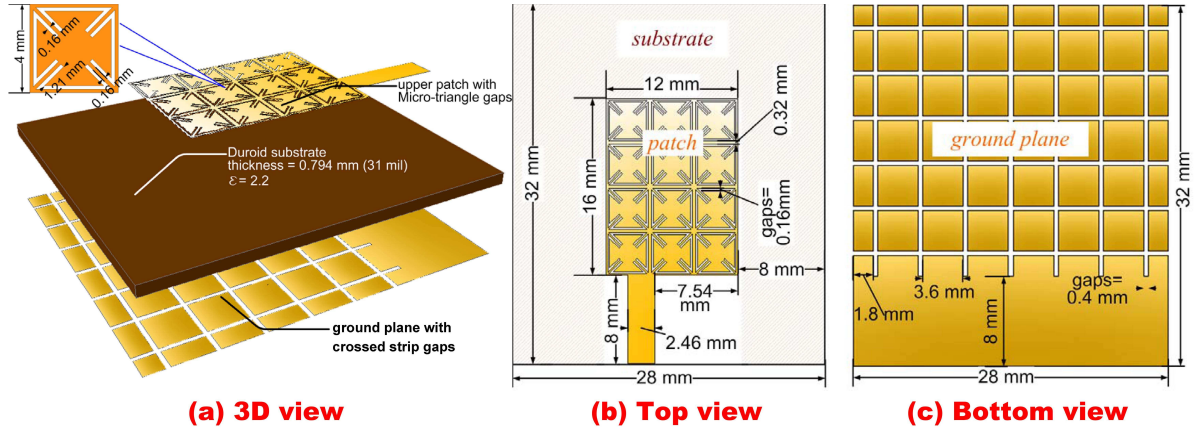


Figure 1: (Color online) Configuration in 3D of the proposed patch antenna.

microstrip line. The substrate used here is Duroid with a relative permittivity of $\epsilon_r = 2.2$, and its thickness is 31 mil. The area of the upper patch mounted is $12 \times 16 \text{ mm}^2$. Two different widths g of the gaps (i.e., 0.3 mm and 0.4 mm) on the ground plane are assumed. Therefore, different inductance components of the LHM characteristics can be obtained so as to control the resonance frequency and also the working bandwidth of the designed antenna.

It is realized that the patterned ground plane produces negative permeability in the first frequency bandwidth while the patterned patch antenna produces negative permittivity in the second frequency bandwidth. (a) If only the patterned ground plane or the patterned patch antenna is utilized, then only single negative medium effect can be observed and it produces the stop-band. Therefore, both the patterned ground plane and the patterned patch antenna are used. (b) If the double negative permittivity and permeability fall within different bandwidths and there is no overlap, then it still produces the stop-band. (c) If the double negative permittivity and permeability fall within the same bandwidth or there is big overlap between the two bandwidths, then it produces the pass-band so that the energy can be radiated by the antenna. Of course, the impedance matching should be always considered.

The prototypes LHM patch antenna was numerically simulated/designed, physically fabricated, practically measured and comparatively studied with theoretical results. To optimize it for various parameters, a full wave finite element method simulator was used. The computed S_{11} values of the proposed antenna and the reference patch antenna are obtained and shown in Fig. 2(a). As seen, the working bandwidth of the conventional patch antenna is 200 MHz (between 7.1 GHz and 7.3 GHz), which is typically very narrow as expected but serves as a benchmark for the improved designs. The proposed antenna is designed to have the 0.4 mm gap at the bottom, and the -10 dB bandwidth (which is standardly defined for engineering applications) falls within 5.3 GHz and 8.5 GHz (which is 3.2 GHz in bandwidth, and is 16 times wider than the conventional antenna). When the gap at the bottom becomes 0.3 mm, the -10 dB bandwidth turns within 5.7 GHz and 8.6 GHz (which is 2.9 GHz in bandwidth, and is 14.5 times wider than the conventional antenna).

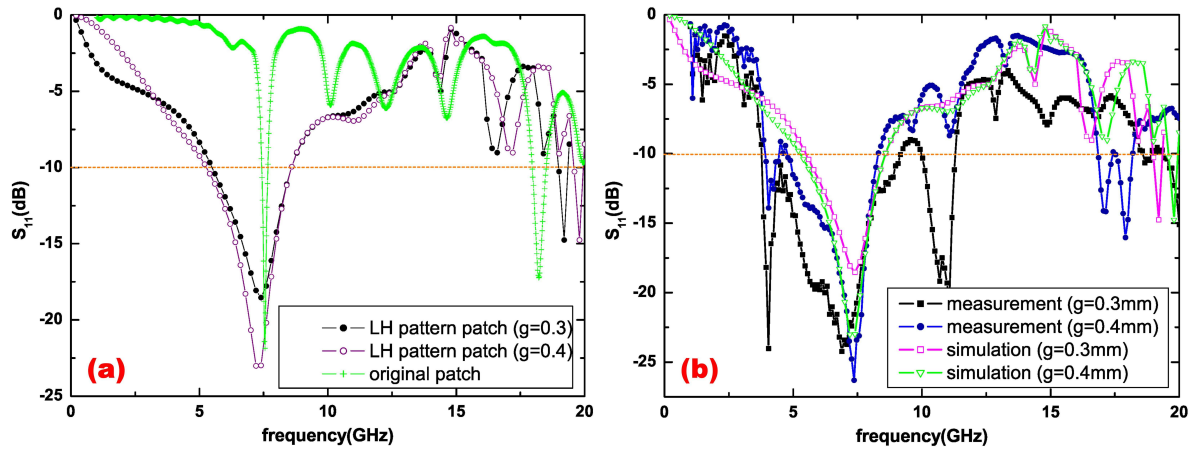


Figure 2: (Color online) S -parameter values of the proposed antenna with different gap widths. (a) Computed S_{11} values for metamaterial antenna and conventional patch. (b) Measured and computed S_{11} values for metamaterial antennas.

To verify the accuracy of designs, two proposed antennas with different gap widths (one of which is shown in Fig. 3) are then fabricated and measured. Experimental results of S_{11} values are compared with numerically predicted results in Fig. 2(b). The general variational trace of the experimental results follows closely to that of the simulated S_{11} values. From the -10 -dB level line, it is seen that a reasonably good agreement between the design working bandwidth and the measured bandwidth is found. In fact, the fabricated antennas have even wider bandwidths than those of modeled antennas.

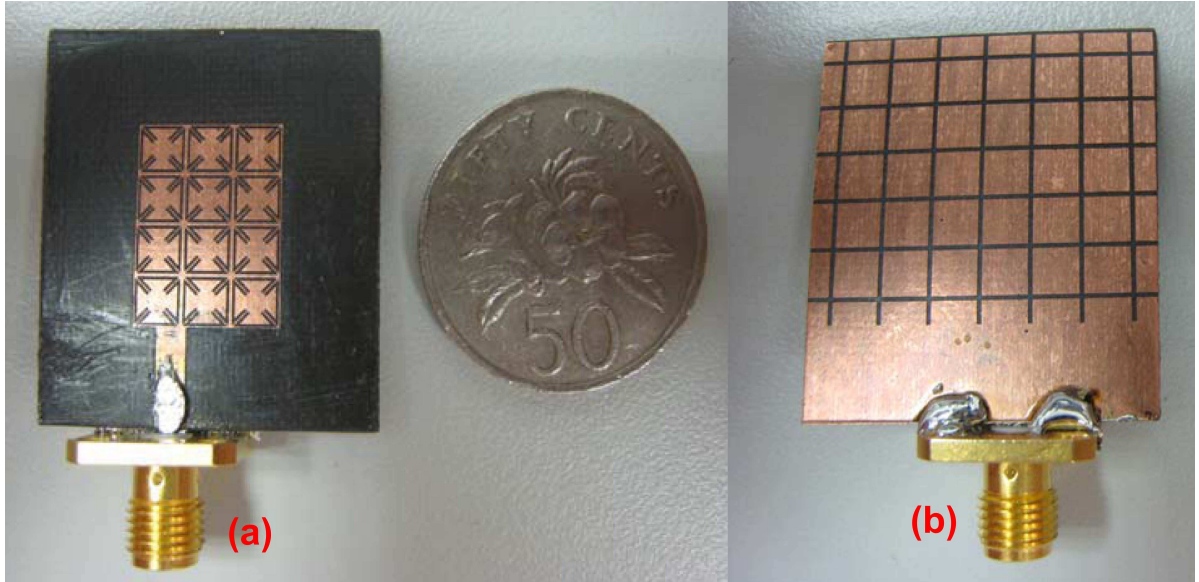


Figure 3: (Color online) (a) Top and (b) bottom views of a fabricated patch antenna.

Antenna gains are measured within the entire frequency band as shown in Fig. 4(a).

The antenna gain is generally above 4 dB with the peak of 7.2 dB. For a patch antenna, this has been a very high as compared with that of a standard one. The voltage standing

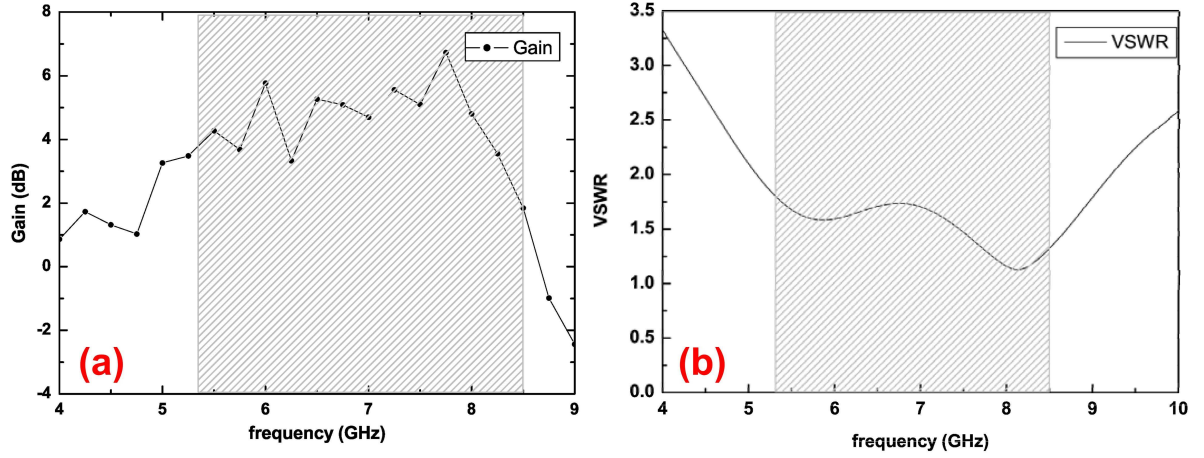


Figure 4: (Color online) (a) Measured gain and (b) simulated VSWR of proposed antenna with a gap of 0.4 mm. Shaded area shows the working band.

wave ratio (VSWR) is defined as $(1 + |\Gamma|)/(1 - |\Gamma|)$ where Γ denotes the reflection coefficient. The VSWR value serves as a good measure to check if the system is working efficiently. In the present work, the simulated VSWR value is well below 2 (which serves as a good reference value for most of the engineering applications) within the frequency band as shown in Fig. 4(b).

Due to the left-handed transmission characteristics, the wave propagation along the patch induces the strongest radiation in horizontal direction instead of the vertical direction of the conventional patch antenna. To further confirm this, two frequencies, i.e., 6.66 GHz and 7.77 GHz both in the working bandwidth, are randomly chosen to characterize radiation of the antenna. According to the computed results, the 3D radiation patterns at these two frequencies are shown in Fig. 5. It is apparent that energy radiates to the horizontal directions.

To further verify the results, the measured co-polarization and cross-polarization radiation patterns are plotted in 2D in Fig. 6, respectively. The gain is found to be able to reach as high as 7.14 dB, which is quite desirable for a single patch and it would never happen if a conventional patch antenna is designed. Also seen from the 2D patterns at both of these randomly picked frequencies, the radiated energy is mainly focused in the x -direction in the case of the co-polarization. In the case of the cross-polarization, the radiation level is well suppressed except at around 210° of the θ -direction in the xy -plane. So we may also take a good advantage of this special characteristic to transmit two quadrature signals using the antenna as a directional one for beam control.

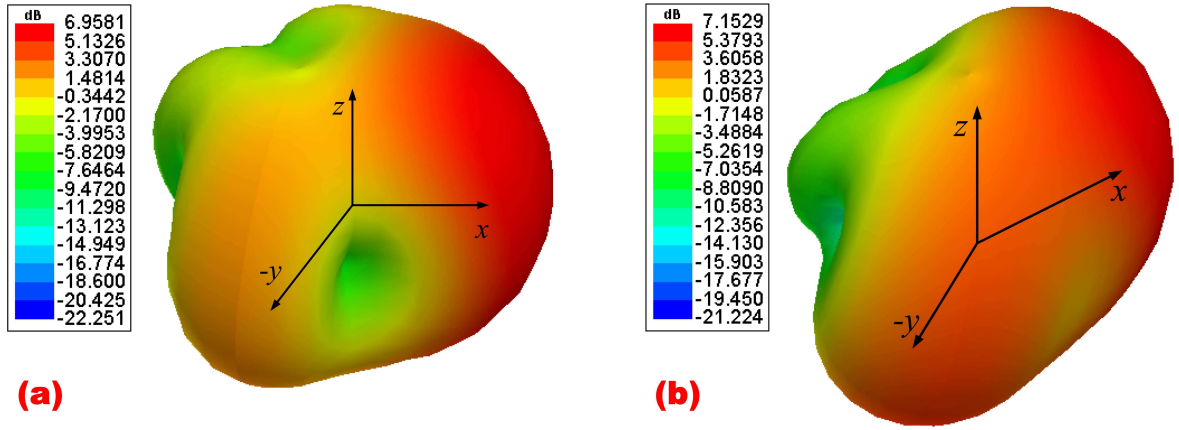


Figure 5: (Color online) Computed 3-D radiation patterns at (a) 6.66 GHz and (b) 7.77 GHz, respectively.

0.5 Metamaterial Microstrip Antenna Arrays

After we successfully designed the single patch element, we then move to design the metamaterial microstrip array. The 4-element microstrip array is of the size (88 mm \times 30 mm) and fed by a microstrip line network, as shown in Fig. 7 [28,29].

Table 1: Computed antenna gains versus number of elements and operating frequency.

Freq	4 ele.	5 ele.	6 ele.	7 ele.	8 ele.	9 ele.	10 ele.
6.50 G	8.6209	9.5597	10.314	10.940	11.469	11.932	12.316
6.70 G	8.9418	9.8778	10.629	11.250	11.776	12.226	12.615
7.27 G	9.6686	10.599	11.343	10.940	11.469	11.923	13.281
7.70 G	10.007	10.932	11.670	12.276	12.783	13.210	13.574
7.80 G	10.066	10.990	11.727	12.331	12.835	13.261	13.622

From the radiation pattern of the single patch element, we make the array along the $\phi = 90^\circ$ direction. From the design, it is found that the bandwidth can be larger than 1.5 GHz. The gain is also very high, as seen in Table 1 where the array is matched ideally, depending upon the number of elements (varying from 4 to 10 elements) and the operating frequency (changing from 6.5 to 7.8 GHz). Then, array with power divider networks as shown in Fig. 7 is analyzed, the return loss of the proposed array is compared with the computed results of the original array in Fig. 8, the bandwidth (Return loss 10 dB level) of the proposed array is larger than 2.8 GHz. For surface waves exist between antenna elements designed above, which propagate along the microstrip and couple to patch elements, which takes a great influence to the radiation and input characteristics of the array. The influence

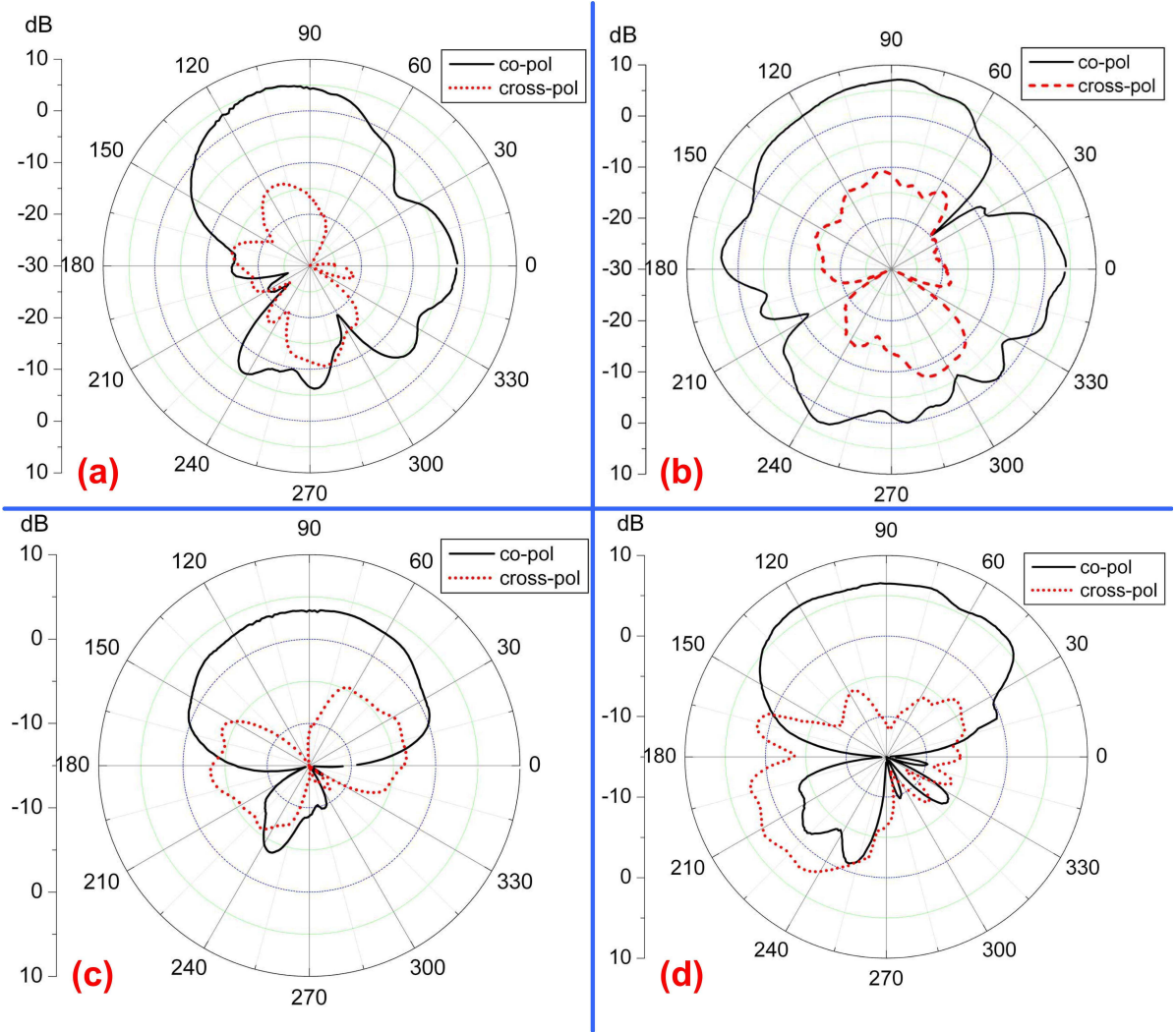


Figure 6: (Color online) Measured radiation patterns of co-polarization (solid line) and cross-polarization (dotted line) (a) at 6.66 GHz in the xy -plane; (b) at 7.77 GHz in the xy -plane; (c) at 6.66 GHz in the yz -plane; and (d) at 7.77 GHz and in the yz -plane, respectively.

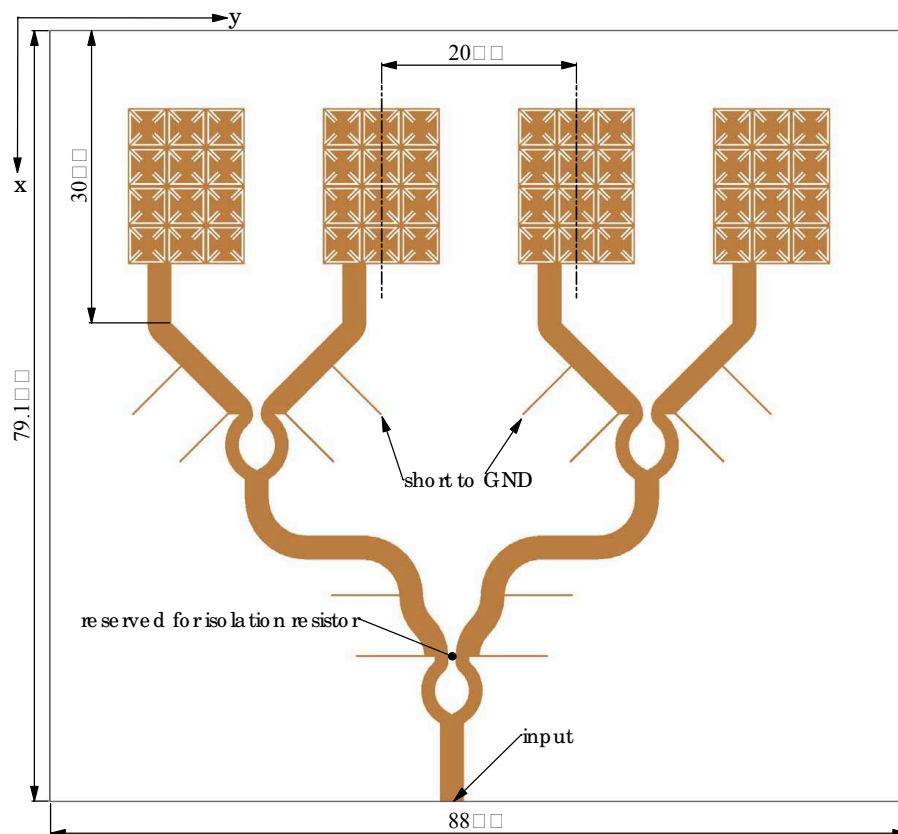


Figure 7: Microstrip antenna array geometry.

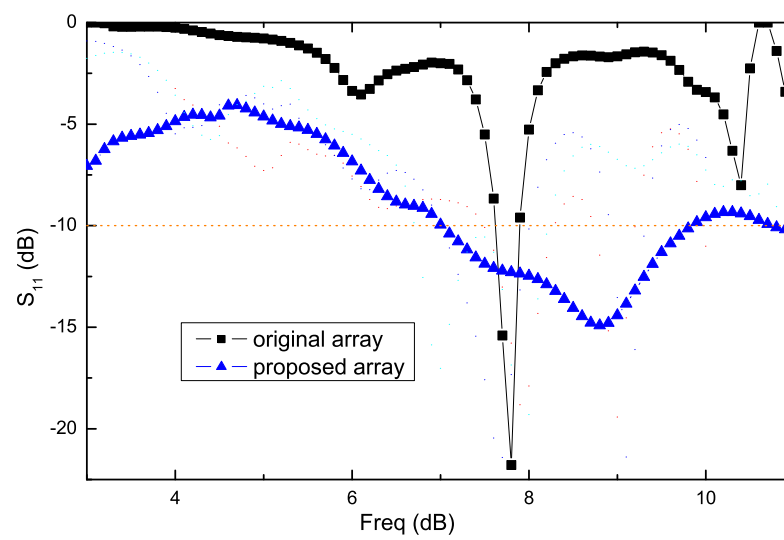


Figure 8: Computed return loss of the 4-element array.

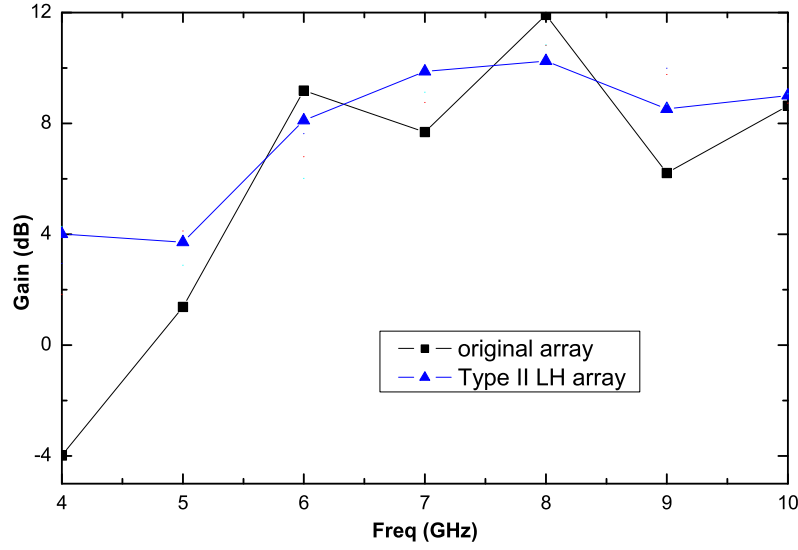


Figure 9: Computed antenna gains versus operating frequency.

of surface waves can be reduced by introducing insulation technique between elements, such as adding some band gap structures [30,31].

Fig. 9 shows the computed gain of the proposed array and the original array, the original array also have high gain, but when the frequency is below about 7.1 GHz or higher than about 8.9 GHz, radiation pattern changed a lot, for some leaky modes and high modes are excited, and the maximum radiation direction of leaky modes changed with frequency [32,33], so as the radiation pattern changed. The radiation pattern of the proposed array remains good in the frequency range of 5.5 GHz to 9.2 GHz as shown in Fig. 10.

In frequency of 8.2 GHz, the ϕ and θ components of radiation pattern in $\theta = 90^\circ$ plane of the proposed array are plotted in Fig. 11. Similar to the single antenna element, the main radiation direction in $\theta = 90^\circ$ plane (in far-field) is ϕ direction. It is found that the antenna array patterns are consistently strong in the horizontal plane, as expected for the entire working frequency bandwidth. The radiation pattern remains radiation in patch direction in a broadband frequency.

0.6 New Physics of the Present Work and Future Applications

In this project, we have proposed and implemented a new idea of using the negative permittivity and negative permeability of the circuitry in the microstrip antennas and microstrip

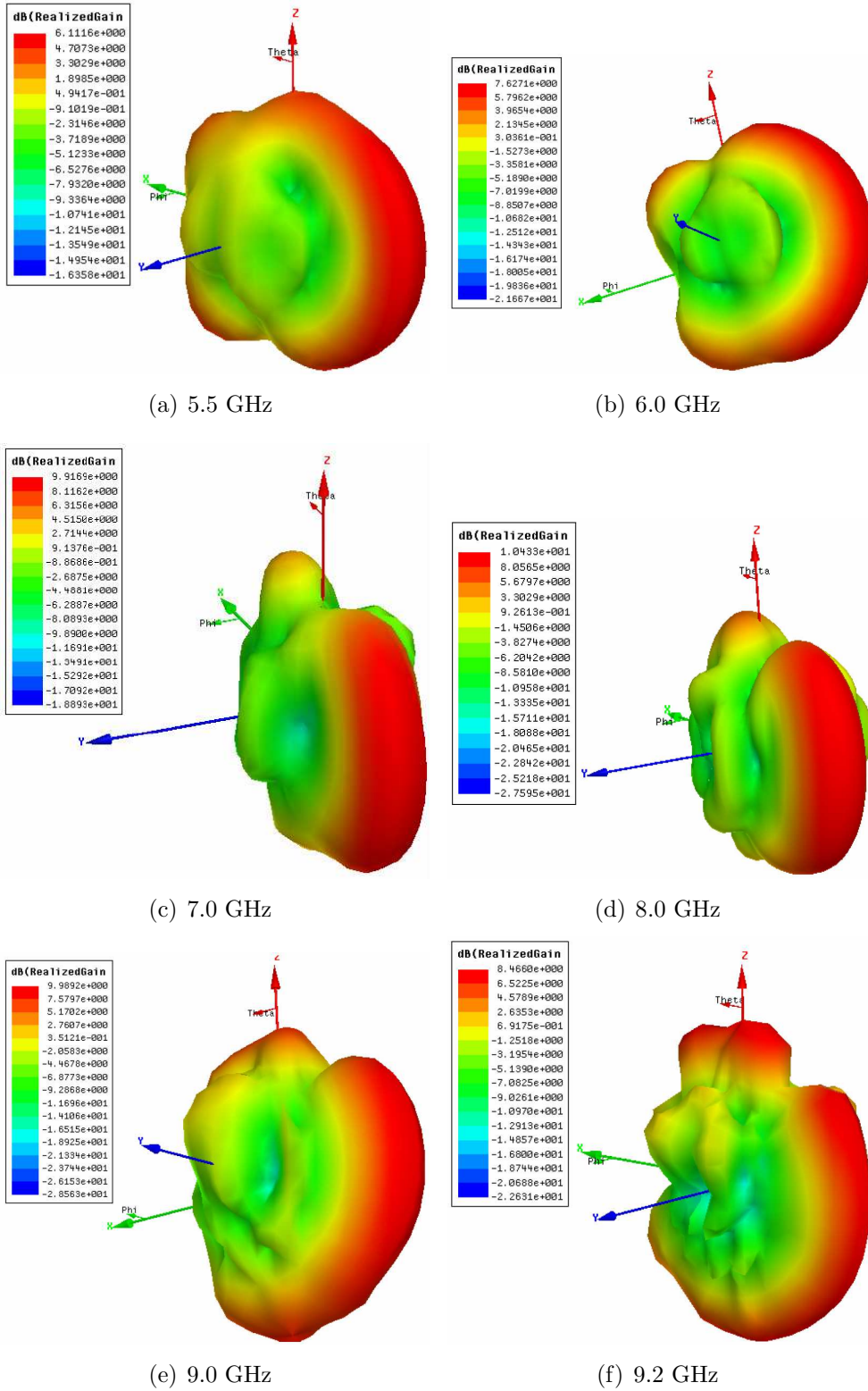


Figure 10: Computed 3-D radiation patterns of the antenna array with 4 elements.

antenna arrays into their practical applications. The new antennas, now known as the metamaterial microstrip antennas and arrays or metamaterial flower antennas and arrays, are

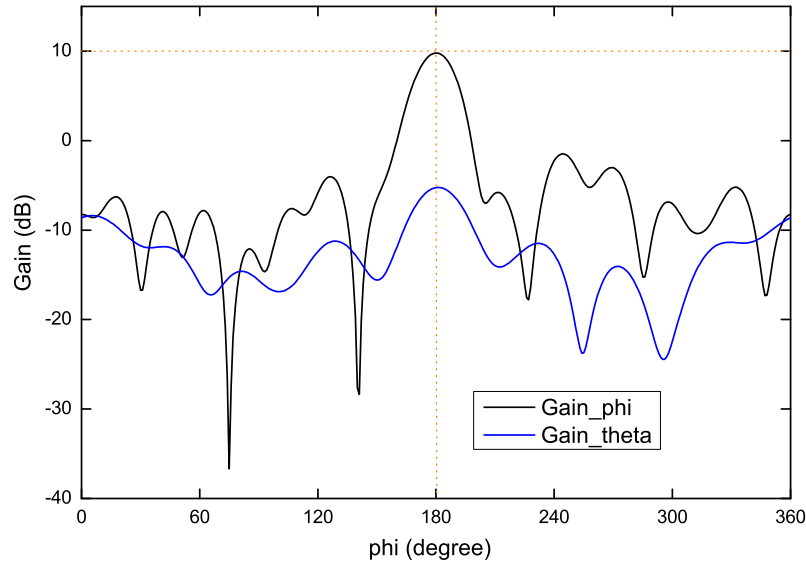


Figure 11: Radiation components in $\theta = 90^\circ$ plane of 8.2 GHz.

found to have much broader frequency bandwidths and also high gains.

There are a few points which need to be addressed clearly. In the present antenna design, the primary idea used is the metamaterial concepts where the antenna substrate material itself is still a conventional one.

- From this point of view, the design concept is very different from those designs where the electromagnetic bandgap (EBG) structures or materials are employed. The EBG structures were utilized in the design and fabrication of microstrip antennas and arrays so that the surface waves propagating along the microstrip patch(es) can be suppressed, and therefore the total radiation efficiency can be enhanced significantly toward the direction normal to the patches. The present design in fact fully utilizes the properties of the surface waves so that the radiation can be enhanced towards the same direction of the surface waves.
- Secondly, the design concept is also very different from the frequency selective surface (FSS) idea. The FSS periodic structures are of very strictly designed patterns so that the responses of the FSS structures can meet the specific requirements by the system components. In the metamaterial antenna design, the periodic patterns are also integrated inside the designs, but it does not require the pure periodicity of the patterns. Also the purpose of employing periodic patterns in the metamaterial designs are entirely different from the FSS structures.

In short, a new concept of negative index materials (NIM) was used in the design of the metamaterial antennas. It is different from either the frequency selective surface concept or the electromagnetic bandgap concept. The performance of the metamaterials designed is found better than those antennas designed using the EBG concept, while the FSS concept was usually applied to make optimized radar cross section designs of air or ocean vehicles or objects.

As the metamaterial flower antennas are proved to have high performance, therefore, it is expected that the concept can be applied to the future practical antenna designs. So, the future work will be applications of the optimally designed metamaterial antennas for practical applications, especially the defence applications. The next work might be the demonstration project to be proposed for the defense component designs.

0.7 Conclusions

A novel broad bandwidth microstrip antenna and also an array of this kind are proposed and designed using the metamaterial concept via the pattern-etched upper patches and bottom ground plane which form a C-L equivalent circuit of negative index for enhancing the antenna array performance. Some simulated and measured results are obtained and the working frequency bandwidth of the rectangular microstrip antenna and array are significantly broadened from about 200 MHz to about 3 GHz (at about 8-15 times). Also, this new patch antenna designed using the metamaterial concept has very high efficiency of above 98% according to simulation, very low loss (or high gain according to measurements) and low voltage standing wave ratio.

Practical experiments demonstrate a reasonably good agreement between simulation and measurement results of the S-parameters and the antenna patterns. Both theoretically and experimentally, it is depicted that the antenna could radiate toward the horizontal directions within the entire working frequency band, while the vertical radiation is well suppressed — which could lead many practical applications in wireless communication subsystems.

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